HERMETIC PACKAGES AND FEEDTHROUGHS FOR NEURAL PROSTHESES

Quarterly Progress Report # 2

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SUMMARY

During the past quarter we continued testing of the silicon-glass packages under accelerated conditions, fabricated and characterized a polyimide-based relative humidity sensor, and continued our efforts in remote monitoring of humidity inside the glass packages using telemetry .

Our most significant package testing results to date are those obtained from a series of silicon-glass packages that have been soaking in DI water at 85°C and 95°C for more than 3 years. We reported in the last progress reports that all packages soaking at 95°C had failed. There were also 4 packages that were soaking at 85°C. Of these four, three packages are still dry and under test. Of the original 10 packages, the longest going sample has reached a maximum of 1444 days at 85°C and 484 days at 95°C. If we assume that all of the packages at 85°C failed the same time that the 95°C packages failed, we can calculate a worst case mean time to failure of 258 days for the samples at 85°C, and of 119 days for the samples soaking at 95°C. The worst case MTTF at body temperature based on these tests is then calculated to be 58 years. These tests have been very encouraging and clearly indicate the packages can last for many years in water. In addition to these tests in DI water, we had also soaked several packages in saline at the above two temperatures. The results obtained from these tests were reported in the last progress report. We also have had 4 packages soaking at room temperature in saline. The longest lasting package has been soaking for 1344 days, and an average soak period of 1100 days at room temperature. We will continue to observe these packages for any sign of leakage. A new set of package tests had also been initiated in the previous quarter at 85 and 95°C. At each temperature, eight packages, that had been coated with silicone rubber to prevent premature dissolution of the top polysilicon bonding layer, were soaked. These tests have provided a MTTF of 217 days at 85°C, and 125 days at 95°C, and these results indicate again the problem we have had with the dissolution of the polysilicon film. However, these results also show that the silicone coating significantly increases the time to failure of these coated packages.

A polyimide thin film relative humidity sensor based on a simple capacitive structure has been fabricated and extensive tests have been performed to characterize this sensor. This relative humidity sensor not only withstands the anodic bonding process parameters, but also shows very little drift at body temperature. Our tests so far show that it meets our requirements well and will be used to monitor humidity inside silicon-glass packages in actual animal experiments.

We have also completed the modeling and study of a simple telemetry technique for remote monitoring of changes in dew point inside the package. This is based on an integrated on-chip coil which is inductively coupled to an external transmitter coil. Further tests are being conducted to determine whether changes in the impedance of the dew point sensor can be detected reliably using the external transmitter without the need for an integrated internal transmitter. Additional results will be provided in the coming quarter.

I. INTRODUCTION

This project aims at the development of hermetic, biocompatible micropackages and feedthroughs for use in a variety of implantable neural prostheses for sensory and motor handicapped individuals. In addition, it will also develop a telemetry system for monitoring package humidity in unrestrained animals, and of telemetry electronics and packaging for stimulation of peripheral nerves. The primary objectives of the proposed research are: 1) the development and characterization of hermetic packages for miniature, silicon-based, implantable neural prostheses designed to interface with the nervous system for many decades; 2) the development of techniques for providing multiple sealed feedthroughs for the hermetic package; 3) the development of custom-designed packages and systems used in several different chronic stimulation or recording applications in the central or peripheral nervous systems in collaboration and cooperation with groups actively involved in developing such systems; and 4) establishing the functionality and biocompatibility of these custom-designed packages in *in-vivo* applications. Although the proposed research is focused on the development of the package and feedthroughs, it also aims at the development of inductively powered systems that can be used in many implantable recording and stimulation devices in general, and of multichannel microstimulators for functional neuromuscular stimulation, and multichannel recording microprobes for CNS applications in particular.

Our group here at the Center for Integrated Sensors and Circuits at the University of Michigan has been involved in the development of silicon-based multichannel recording and stimulating microprobes for use in the central and peripheral nervous systems. More specifically, during the past three contract periods dealing with the development of a single-channel inductively powered microstimulator, our research and development program has made considerable progress in a number of areas related to the above goals. A hermetic packaging technique based on electrostatic bonding of a custom-made glass capsule and a supporting silicon substrate has been developed and has been shown to be hermetic for a period of at least a few decades in salt water environments. This technique allows the transfer of multiple interconnect leads between electronic circuitry and hybrid components located in the sealed interior of the capsule and electrodes located outside of the capsule. The glass capsule can be fabricated using a variety of materials and can be made to have arbitrary dimensions as small as 1.8mm in diameter. A multiple sealed feedthrough technology has been developed that allows the transfer of electrical signals through polysilicon conductor lines located on a silicon support substrate. Many feedthroughs can be fabricated in a small area. The packaging and feedthrough techniques utilize biocompatible materials and can be integrated with a variety of micromachined silicon structures.

The general requirements of the hermetic packages and feedthroughs to be developed under this project are summarized in Table 1. Under this project we will concentrate our efforts to satisfy these requirements and to achieve the goals outlined above. There are a variety of neural prostheses used in different applications, each having different requirements for the package, the feedthroughs, and the particular system application. The overall goal of the program is to develop a miniature hermetic package that can seal a variety of electronic components such as capacitors and coils, and integrated circuits and sensors (in particular electrodes) used in neural prostheses. Although the applications are different, it is possible to identify a number of common requirements in all of these applications in addition to those requirements listed in Table 1. The packaging and feedthrough technology should be capable of:

1- protecting non-planar electronic components such as capacitors and coils, which typically have large dimensions of about a few millimeters, without damaging them;
2- protecting circuit chips that are either integrated monolithically or attached in a hybrid fashion with the substrate that supports the sensors used in the implant;
3- interfacing with structures that contain either thin-film silicon microelectrodes or conventional microelectrodes that are attached to the structure;

Table 1: General Requirements for Miniature Hermetic Packages and Feedthroughs for Neural Prostheses Applications

Package Lifetime:

≥ 40 Years in Biological Environments @ 37°C

Packaging Temperature:

≤360°C

Package Volume:

10-100 cubic millimeters

Package Material:

Biocompatible

Transparent to Light

Transparent to RF Signals

Package Technology:

Batch Manufactureable

Package Testability:

Capable of Remote Monitoring

In-Situ Sensors (Humidity & Others)

Feedthroughs:

At Least 12 with ≤125μm Pitch

Compatible with Integrated or Hybrid Microelectrodes

Sealed Against Leakage

Testing Protocols:

In-Vitro Under Accelerated Conditions

In-Vivo in Chronic Recording/Stimulation Applications

We have identified two general categories of packages that need to be developed for implantable neural prostheses. The first deals with those systems that contain large components like capacitors, coils, and perhaps hybrid integrated circuit chips. The second deals with those systems that contain only integrated circuit chips that are either integrated in the substrate or are attached in a hybrid fashion to the system.

Figure 1 shows our general proposed approach for the package required in the first category. This figure shows top and cross-sectional views of our proposed approach here. The package is a glass capsule that is electrostatically sealed to a support silicon substrate. Inside the glass capsule are housed all of the necessary components for the system. The electronic circuitry needed for any analog or digital circuit functions is either fabricated on a separate circuit chip that is hybrid mounted on the silicon substrate and electrically connected to the silicon substrate, or integrated monolithically in the support silicon substrate itself. The attachment of the hybrid IC chip to the silicon substrate can be performed using a number of different technologies such as simple wire bonding between pads located on each substrate, or using more sophisticated techniques such as flip-chip solder reflow or tab bonding. The larger capacitor or microcoil components are mounted on either the substrate or the IC chip using appropriate epoxies or solders. This completes the assembly of the electronic components of the system and it should be possible to test the system electronically at this point before the package is completed. After testing, the system is packaged by placing the glass capsule over the entire system and bonding it to the silicon substrate using an electrostatic sealing process. The cavity inside the glass package is now hermetically sealed against the outside environment. Feedthroughs to the outside world are provided using the grid-feedthrough technique discussed in previous reports. These feedthroughs transfer the electrical signals between the electronics inside the package and various elements outside of the package. If the package has to interface with conventional microelectrodes, these microelectrodes can be attached to bonding pads located outside of the package; the bond junctions will have to be protected from the external environment using various polymeric encapsulants. If the package has to interface with on-chip electrodes, it can do so by integrating the electrode on the silicon support substrate. Interconnection is simply achieved using on-chip polysilicon conductors that make the feedthroughs themselves. If the package has to interface with remotely located recording or stimulating electrodes that are attached to the package using a silicon ribbon cable, it can do so by integrating the cable and the electrodes again with the silicon support substrate that houses the package and the electronic components within it.

Figure 2 shows our proposed approach to package development for the second category of applications. In these applications, there are no large components such as capacitors and coils. The only component that needs to be hermetically protected is the electronic circuitry. This circuitry is either monolithically fabricated in the silicon substrate that supports the electrodes (similar to the active multichannel probes being developed by the Michigan group), or is hybrid attached to the silicon substrate that supports the electrodes (like the passive probes being developed by the Michigan group). In both of these cases the package is again another glass capsule that is electrostatically sealed to the silicon substrate. Notice that in this case, the glass package need not be a high profile capsule, but rather it need only have a cavity that is deep enough to allow for the silicon chip to reside within it. Note that although the silicon IC chip is originally 500μm thick, it can be thinned down to about 100μm, or can be recessed in a cavity created in the silicon substrate itself. In either case, the recess in the glass is less than 100μm deep (as opposed to several millimeters for the glass capsule). Such a glass package can be easily fabricated in a batch process from a larger glass wafer.

The above two approaches address the needs for most implantable neural prostheses. Note that both of these techniques utilize a silicon substrate as the supporting base, and are not directly applicable to structures that use other materials such as ceramics or metals. Although this may seem a limitation at first, we believe that the use of silicon is, in fact, an advantage because it is biocompatible and many emerging systems use silicon as a support substrate.

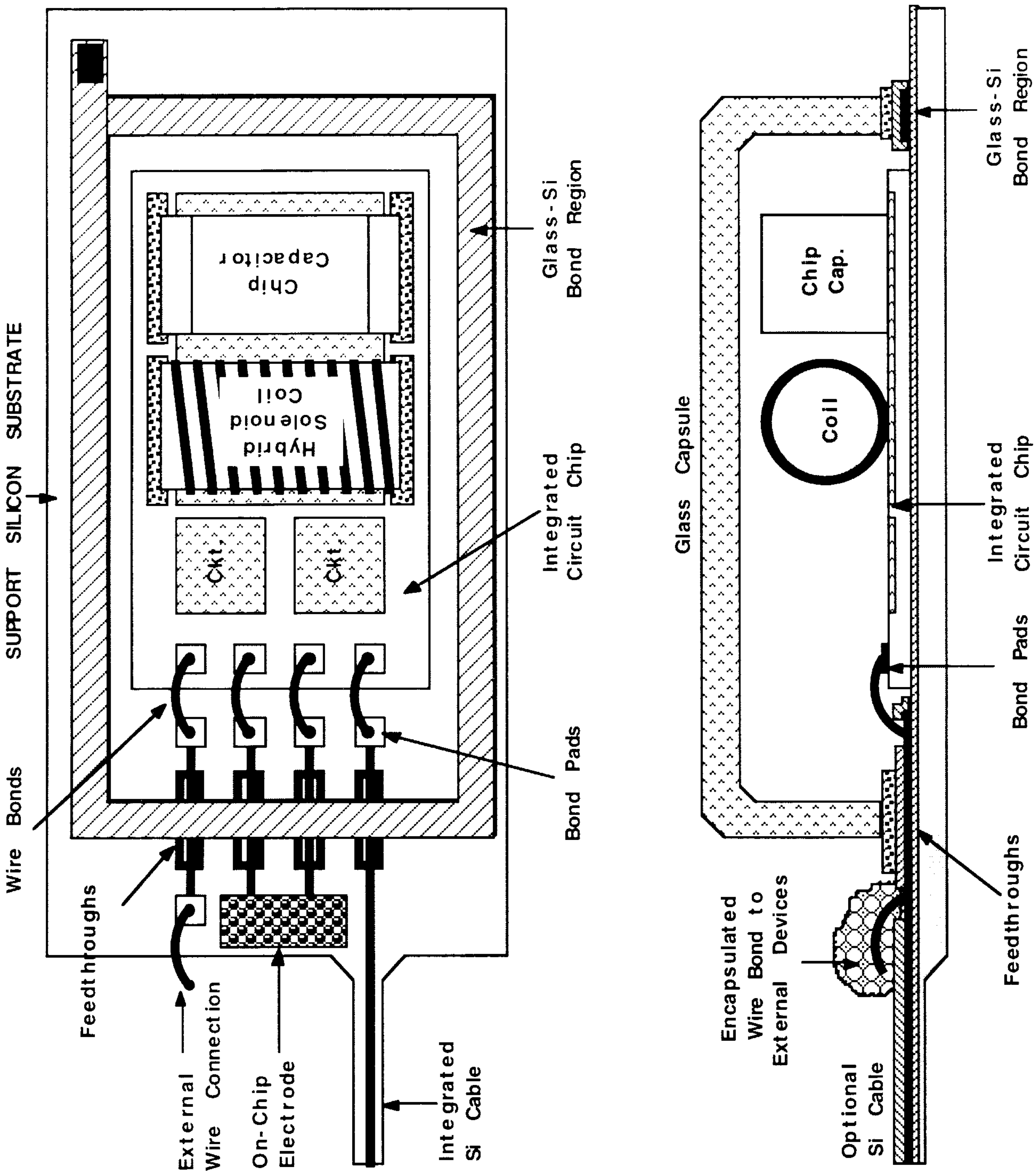

Figure 1: A generic approach for packaging implantable neural prostheses that contain a variety of components such as chip capacitors, microcoils, and integrated circuit chips. This packaging approach allows for connecting to a variety of electrodes.

We will further improve the silicon glass package and its built-in feedthroughs, and will study and explore alternative technologies for hermetic packaging of implantable systems. In particular, we have proposed using a silicon capsule that can be electrostatically bonded to a silicon substrate thus allowing the capsule to be machined down to dimensions below a 100μm. We will also develop an implantable telemetry system for monitoring package humidity in unrestrained animals for a period of at least one year. Two separate systems have been proposed, one based on a simple oscillator, and the other based on a switched-capacitor readout interface circuit and an on-chip low-power AD converter, both using a polyimide-based humidity sensor. This second system will telemeter the humidity information to an outside receiver using a 300MHz on-chip transmitter.

Finally, we have forged potential collaborations with two groups working in the development of recording/stimulating systems for neural prostheses. The first group is that led by Professor Ken Wise at the University of Michigan, which has been involved in the development of miniature, silicon-based multichannel recording and stimulation system for the CNS for many years. Through this collaboration we intend to develop hermetic packages and feedthroughs for a 3-D recording/stimulation system that is under development at Michigan. We will also develop the telemetry front end necessary to deliver power and data to this system. The second group is at Case Western Reserve University, led by Prof. D. Durand, and has been involved in recording and stimulation from peripheral nerves using cuff electrodes. Through this collaboration we intend to develop a fully-integrated, low-profile, multichannel, hermetic, wireless peripheral nerve stimulator that can be used with their nerve cuff electrode. This system can be directly used with other nerve cuffs that a number of other groups around the country have developed. Both of these collaborations should provide us with significant data on the reliability and biocompatibility of the package.

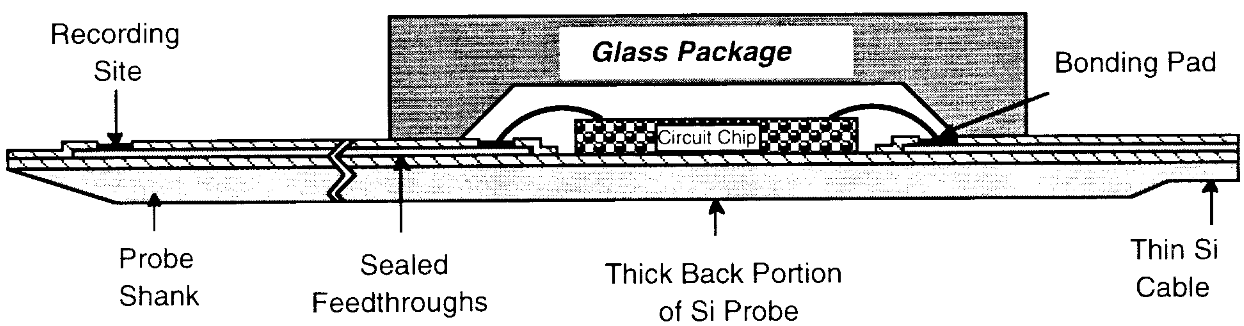

Figure 2: Proposed packaging approach for implantable neural prostheses that contain electronic circuitry, either monolithically fabricated in the probe substrate or hybrid attached to the silicon substrate containing microelectrodes.

II. ACTIVITIES DURING THE PAST QUARTER

2.1 Hermetic Packaging

Over the past few years we have developed a biocompatible hermetic package with high density multiple feedthroughs. This technology utilizes electrostatic bonding of a custom-made glass capsule to a silicon substrate to form a hermetically sealed cavity, as shown in Figure 3. Feedthrough lines are obtained by forming closely spaced polysilicon lines and planarizing them with LTO and PSG. The PSG is reflowed in steam at 1100°C for 2 hours to form a planarized surface. A passivation layer of oxide/nitride/oxide is then deposited on top to prevent direct exposure of PSG to moisture. A layer of fine-grain polysilicon (surface roughness 50A rms) is deposited and doped to act as the bonding surface. Finally, a glass capsule is bonded to this top polysilicon layer by applying a voltage of 2000V between the two for 10 minutes at 320 to 340°C, a temperature compatible with most hybrid components. The glass capsule can be either custom molded from Corning code #7740 glass, or can be batch fabricated using ultrasonic micromachining of #7740 glass wafers.

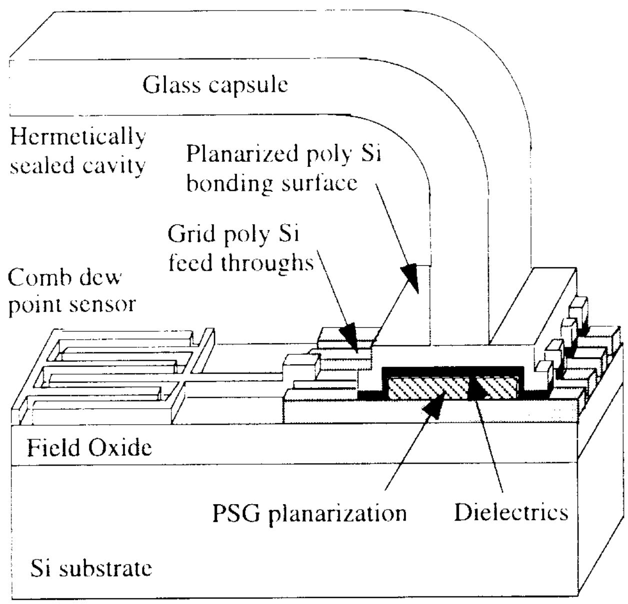

Figure 3: The structure of the hermetic package with grid feedthroughs.

During the past few years we have electrostatically bonded and soak tested over one hundred and sixty of these packages. The bonding yield is about 82% (yield is defined as the percentage of packages which last more than 24 hours in the solution they are soaked in). We should also mention that the earlier tests that have been going for more than about 3 years (room temperature soak tests in saline and the 85°C and the 95°C tests in deionized water) have been made with silicon substrates that are thinned (~150µm) and bonded to the custom molded glass capsules. All of the relatively recent tests (85°C and 95°C tests in saline) are performed with the silicon substrates having full thickness (~500µm) and bonded to the ultrasonically machined glass capsules with a flat top surface. We currently have devices tested in deionized water about 4 years at 85° C, and in saline at room temperature for over 3.7 years. A set of devices has been coated with a silicone coating and was soaked in saline during the 3 previous quarters. These tests have been concluded during this past quarter. The ongoing tests and the concluded tests are detailed in the following sections.

2.1.1 Ongoing Accelerated Soak Tests in Deionized Water

We have continued our accelerated soak tests in deionized water. At the present time, out of the original 20 packages we have 2 packages that have lasted for more than three and a half years with no sign of moisture penetration inside them. In these tests, temperature is chosen as the accelerating factor since it is easy to control and also the diffusion of moisture is a strong (exponential) function of temperature. We had started soaking 10 samples each at 85°C and 95°C. Tables 2 and 3 below list some pertinent data from these soak tests. Figure 4 summarizes the final results from the 95°C soak tests and Figure 5 summarizes the results obtained so far from the 85°C tests. These figures also list the causes of failure for individual packages when it is known, and they show a curve fit to our lifetime data to illustrate the general trend. The curve fit, however, only approximates the actual package lifetimes since some of our packages failed due to breaking during testing rather than due to leakage.

At the beginning of this quarter, we had 2 packages soaking at 85°C. These packages are still dry and under test. For these packages we define failure as the room temperature condensation of moisture inside the package. The testing sequence for these packages starts by cooling the sample to room temperature from its soak bath at the elevated temperature. The samples are next rinsed with deionized water and then carefully dried with a nitrogen gun. We then measure the impedance of the dew point sensors and inspect the sample carefully for leakage under the microscope. The significant change in impedance (about 2 orders of magnitude) and observation of visible condensation inside the package would both be classified as the failure of the package under test.

Of the original 10 samples in the 95°C tests, the longest lasting package survived for a total of 484 days. The calculated mean time to failure of these packages is 135.7 days excluding the handling errors. Of the original 10 packages in the 85°C soak tests there are still 2 with no sign of room temperature condensation. The longest lasting package in the 85°C tests has lasted a total of 1444 days and is still under test. The mean time to failure for these tests has been calculated as 1065 days excluding the handling errors.

Table 2: Key data for 95°C soak tests in DI water.

Number of packages in this study	10
Soaking solution	DI water
Failed within 24 hours (not included in MTTF)	1
Packages lost due to mishandling	2
Longest lasting packages in this study	484 days
Packages still under tests with no measurable room temperature condensation inside	0
Average lifetime to date (MTTF) including losses due to mishandling	*118.7 days*
Average lifetime to date (MTTF) not including losses due to mishandling	*135.7 days*

Table 3: Key data for 85°C soak tests in DI water.

Number of packages in this study	10
Soaking solution	DI water
Failed within 24 hours (not included in MTTF)	2
Packages lost due to mishandling	3
Longest lasting packages so far in this study	1444 days
Packages still under tests with no measurable room temperature condensation inside	2
Average lifetime to date (MTTF) including losses due to mishandling	*676.2 days*
Average lifetime to date (MTTF) not including losses due to mishandling	*1065.2 days*

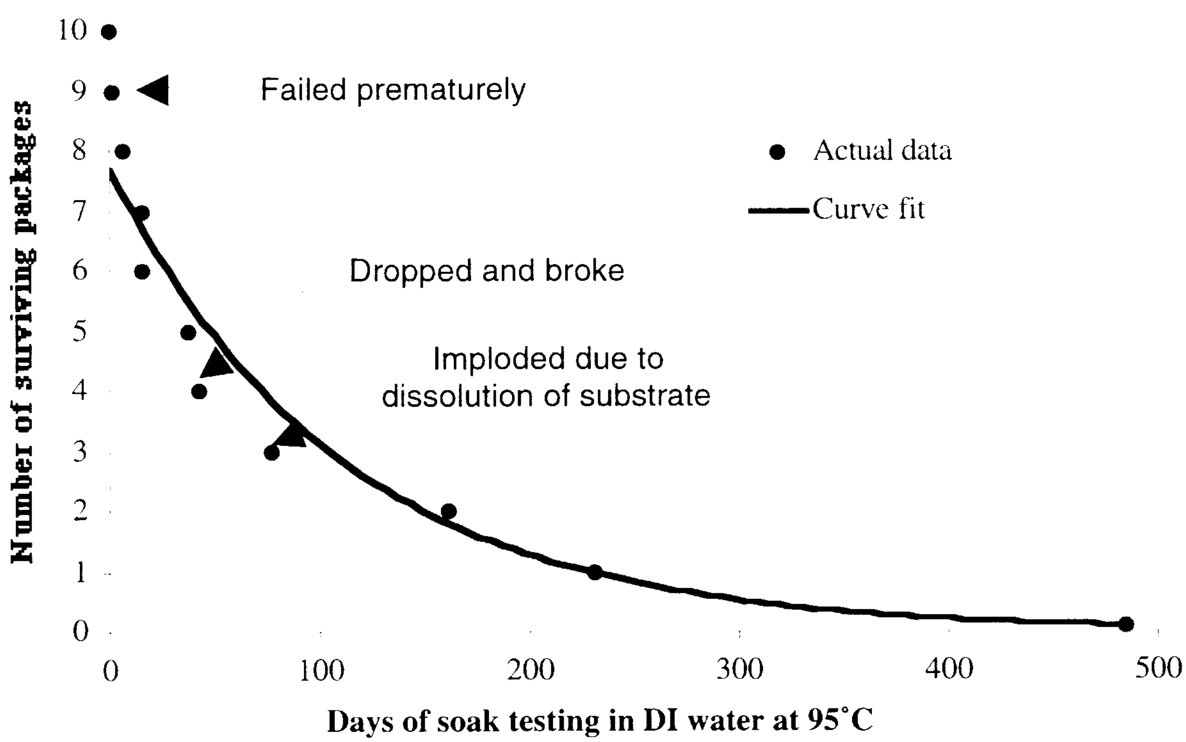

Figure 4: Summary of the lifetimes of the 10 packages that have been soak tested at 95°C in DI water.

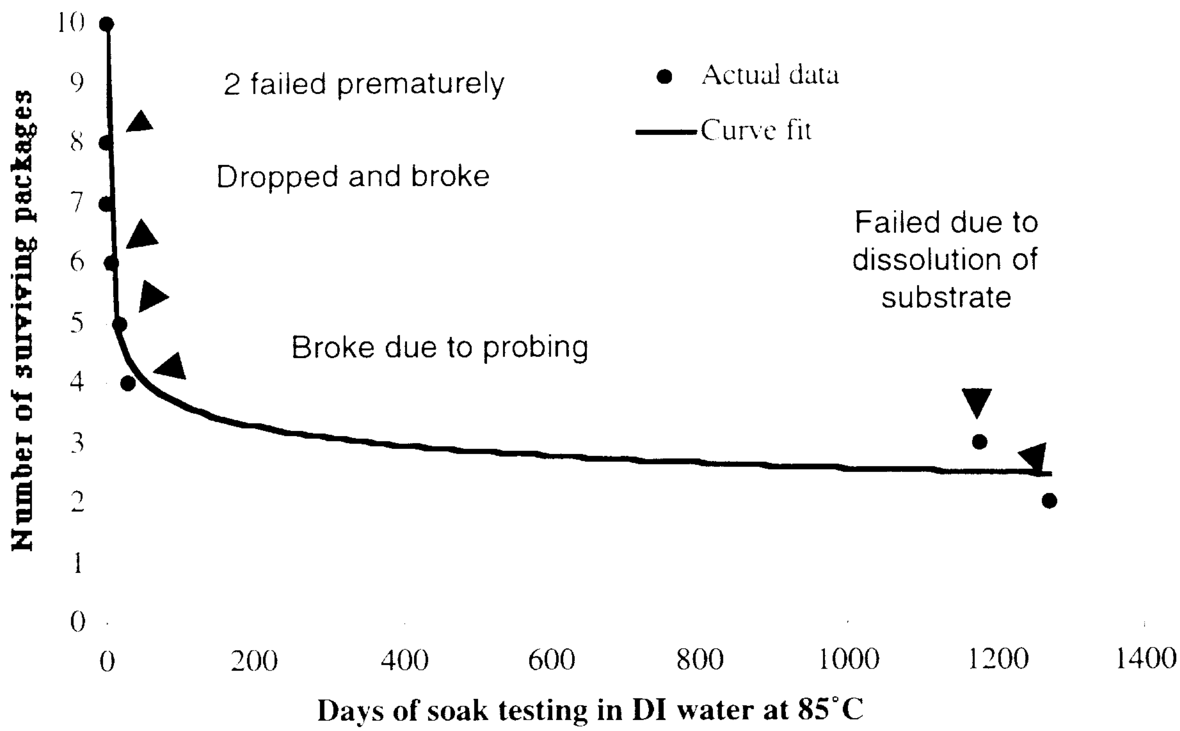

Figure 5: Summary of the lifetimes of the 10 packages that have been soak tested at 85°C in DI water.

2.1.2 Interpretation of Soak Test Results in Deionized Water

Generally during accelerated testing, one models the mean time to failure (MTTF) as an Arrhenius processes (In the VLSI industry this model is used for failure due to diffusion, corrosion, mechanical stress, electromigration, contact failure, dielectric breakdown, and mobile ion/surface inversion). The generalized equation used in all these cases is given below where MTTF is the mean time to failure, A is a constant, ξ is the stress factor other than temperature, (such as pressure or relative humidity), n is the stress dependence, Q is the activation energy, K_B is Boltzman's constant, and T is the temperature in Kelvin.

$$MTTF = A \cdot \xi^{-n} \cdot e^{\left(\frac{Q}{K_B T}\right)}$$

For the accelerated soak tests that we have performed on the packages, there was no stressing factor other than temperature, so the ξ term drops out of the above equation. The resulting equation can be rewritten as a ratio of MTTFs as it is below.

$$AF = \frac{MTTF_{Normal}}{MTTF_{Accelerated}} = e^{\frac{Q}{K_B}\left(\frac{1}{T_{Normal}} - \frac{1}{T_{Accelerated}}\right)}$$

By using these MTTFs at 85°C and 95°C, we can easily calculate the activation energy (Q) and from this activation energy we can proceed to obtain an acceleration factor (AF) for these tests, and then calculate the MTTF at the body temperature. Moreover, after analyzing our failed samples we have found out and mentioned in the past progress reports that some of the samples at the 95°C tests have failed prematurely due to the enhanced dissolution rate for silicon at this temperature. Since the dissolution reaction is an exponential function of temperature, the samples at the 85°C tests have been effected less than the ones at 95°C. The model we use only accounts for acceleration of moisture diffusion, but not dissolution. We will still keep and update the data for the tests performed at 85°C. Moreover, for our calculations we assume that all the samples in the 85°C tests have also failed the same time as the longest going sample in the 95°C tests and proceed with the calculations as follows:

$$MTTF\big|_{85^\circ C} = 257.6\,Days \qquad MTTF\big|_{95^\circ C} = 118.7\,Days$$

Q=0.88 eV, AF(95°C)=179.5, AF(85°C)=82.7

$$MTTF\big|_{37^\circ C} = 58.4\,Years$$

We should also note that we have included every single sample in the 85°C and 95°C soak tests in this calculation except the 15% that failed during the first day (we assume that these early failures can be screened for). Moreover, some of these capsules have failed due to mishandling during testing rather than due to actual leakage into the package. If we disregard the samples that we have attributed failure due to mishandling we obtain a longer mean time to failure:

$$MTTF\big|_{85^\circ C} = 396\,Days \qquad MTTF\big|_{95^\circ C} = 136\,Days$$

Q=1.217 eV, AF(95°C)=1304, AF(85°C)=447

$$MTTF\big|_{37^\circ C} = 485\,Years$$

2.1.3 Accelerated Soak Tests of Silicone-Coated Glass-Silicon Packages in Phosphate Buffered Saline

High temperature testing of 16 silicone-coated package started in September 1997 was concluded during this past quarter because the failure of the last remaining device. As described in the past reports, the purpose of using the silicone coating was to slow down polysilicon etching and hence be able to continue the tests under accelerated conditions. We used a biocompatible silicone coating from Nusil technology, which prevents the ions from reaching the bonding surface. Figure 6 shows a SEM view of our ultrasonically machined glass capsule/silicon package with a silicone rubber coating. As can be seen, the coating material is applied on the interface between the glass capsule and the polysilicon bond. The coated devices were soaked in saline for 11 months at high temperature. Using our acceleration models and the results obtained in our previous testing, we extracted a lifetime for the packages at body temperature.

We started our tests with 8 devices at 85°C and 8 devices at 95°C. Out of the original 8 packages in the 85°C test, one failed after one day (premature failure) due to a fault on the bonding surface which resulted in an incomplete bond between the glass and silicon. This device was not included in our calculations. At the beginning of last quarter, one device was still under test and presented no sign of moisture inside the package. This package failed after being soaked for 315 days, thus concluding this study. Table 4 and Figure 7 give an update and summarize the obtained results.

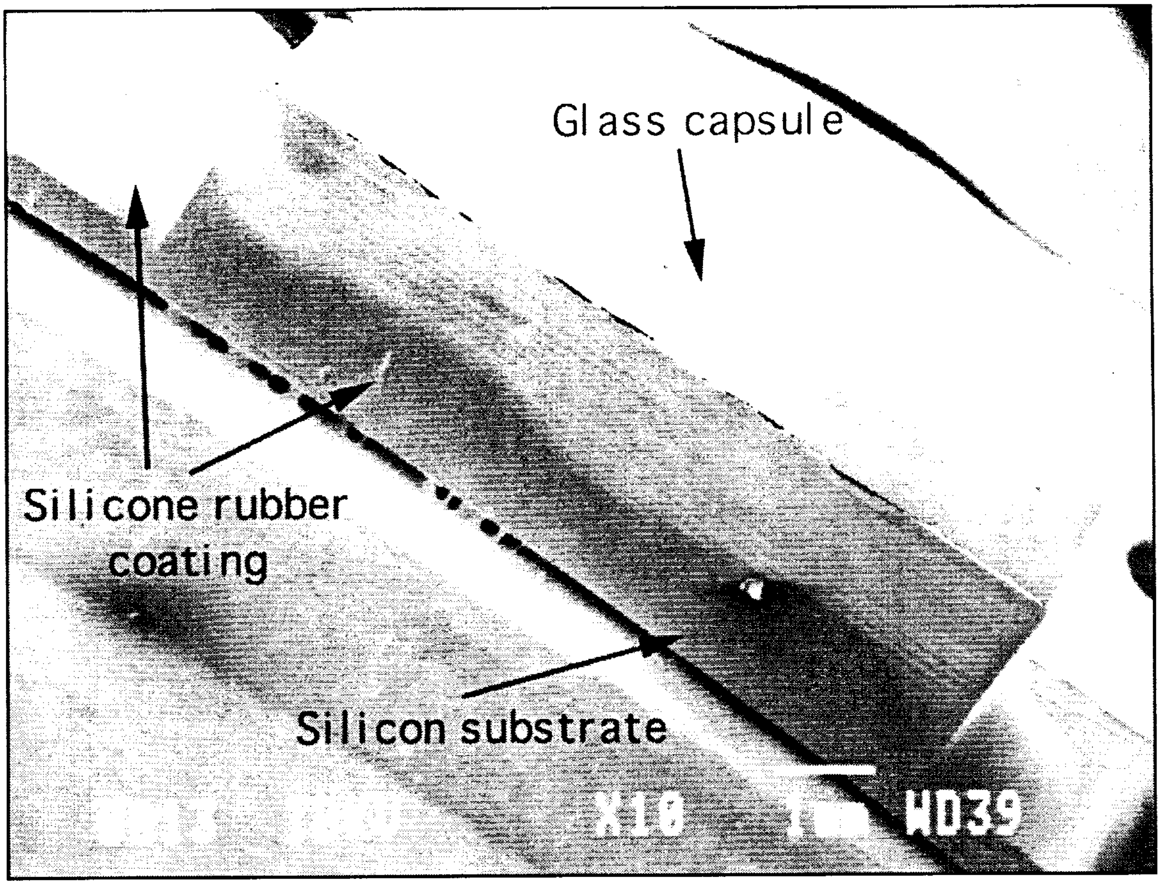

Figure 6: SEM of a silicone-coated glass-silicon package.

Table 4: Key data for soak tests in saline at 85°C.

Number of packages in this study	8
Soaking solution	Saline
Failed within 24 hours (not included in MTTF)	1
Longest lasting packages in this study	315 days
Average lifetime (MTTF)	*217 days*

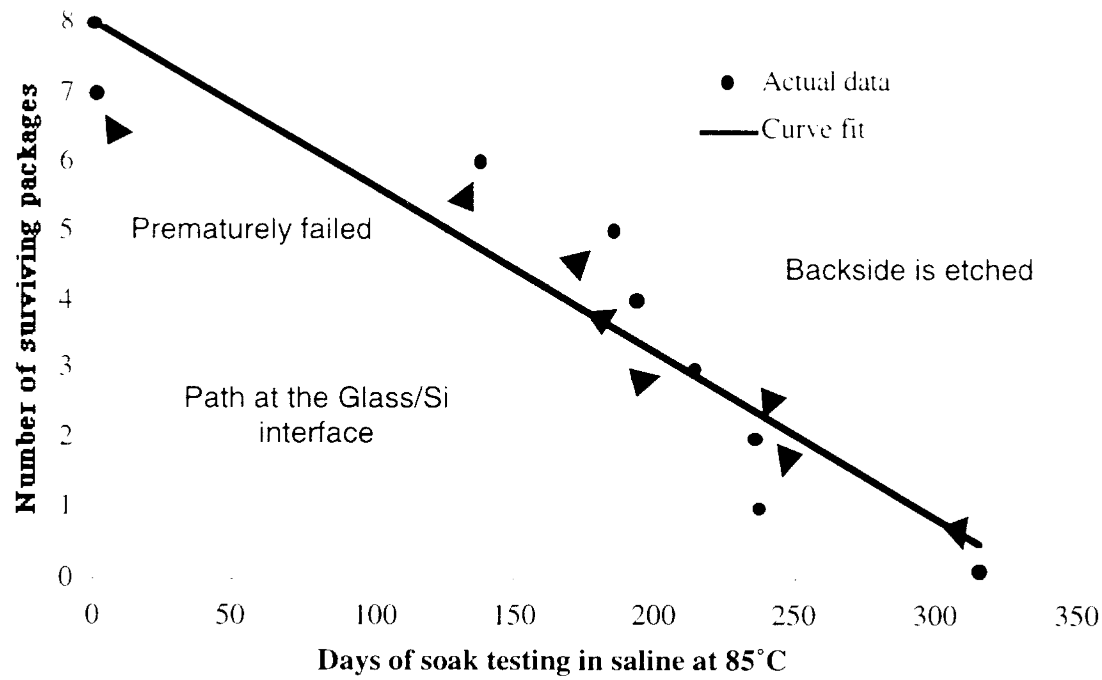

Figure 7: Summary of the lifetime of the 8 packages soaked in saline at 85°C.

Out of the 8 packages soaked at 95°C, one failed after the first day because of a scratch on the polysilicon bonding surface. This package was not included in our calculations. Out of the 7 remaining packages, the first failed after 70 days, the longest lasting package failed after 203 days and we calculated a MTTF of 125 days. Table 5 and Figure 8 give an update and summarize the obtained results.

During these tests, the packages were monitored every few days for room temperature condensation both electrically with integrated dew point sensors (as long as probing was possible) and also visually by the aid of a microscope. With these ultrasonically machined glass capsules, due to their flat top surface, we have the additional advantage of being able to monitor their bonding surface and the glass capsule to polysilicon interface for discoloration and dissolution. When electrical testing of the dew point sensors is possible the failure of a device is defined as condensation at room temperature (the devices are cooled down to room temperature before testing).

Table 5: Key data for soak tests in saline at 95°C.

Number of packages in this study	8
Soaking solution	Saline
Failed within 24 hours (not included in MTTF)	1
Longest lasting packages in this study	203 days
Packages still under tests with no measurable room temperature condensation inside	0
Average lifetime to date (MTTF)	*125 days*

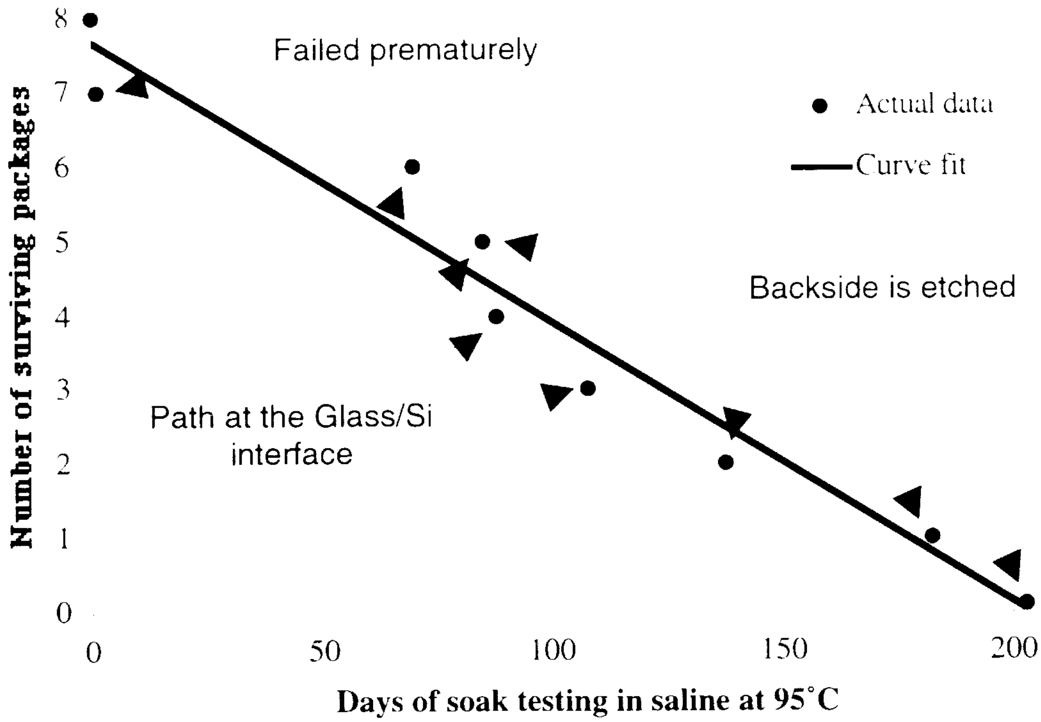

Figure 8: Summary of the lifetime of the 8 packages soaked in saline at 95° C.

The status of the packages during the soaking period was as follows. First, some dissolution is observed around the edges of the devices. In some cases, the dissolution of the probing pads eventually prevents electrical testing of the dew point sensors which are inside the packages. However, visual observation using a microscope allows scanning through the glass capsule for leakage paths on the polysilicon bonding region, and for water penetration or condensation inside the package if a path is created through the substrate or through the interface between silicon and glass. The device is declared failed once a path through the bonding surface or some water inside the package has been observed. In order to overcome the limitations due to the dissolution of the probing pads, we are currently working on developing telemetry techniques used to monitor dew point and humidity inside the package. These techniques are described later in this report.

If we compare the average lifetime of the packages obtained at high temperature in these tests with the previous results obtained with the uncoated devices, we can see a significant improvement due to the silicone rubber coating as summarized in Table 6. For the uncoated devices soaked at 95°C, we had a MTTF of 38 days and the longest lasting package had failed after a mere 70 days. For the devices soaking at 85°C the MTTF has increased from 115.6 days to 217 days. Thus, the silicone coating effectively prevents the corrosion of the top polysilicon layer at high temperatures. This seems to be confirmed by the fact that in the tests of the uncoated devices, the top polysilicon dissolution was the main failure mechanism. In current tests of the coated devices we have also observed failures due to the etching of the substrate itself.

Table 6: Comparisons of the coated and uncoated packages in saline.

Temp.		Coated packages (current tests)	Uncoated packages (past tests)
85 C	Shortest lasting package	138 days	15 days
	Longest lasting package	315 days	321 days
	MTTF	217 days	115.6 days
95 C	Shortest lasting package	70 days	10 days
	Longest lasting package	203 days	70 days
	MTTF	125 days	38 days
Predicted MTTF at body temperature		See next section	117 years

2.1.4 Interpretation of the results obtained for the packages soaked in saline at high temperature

When predicting the Mean Time To Failure at body temperature for the coated devices, if we use the MTTF's obtained above directly in the Arrhenius model that we have used up to now, we obtain a MTTF (37°C) of only 14 years. This number is very small and does not correspond to the 117 year MTTF obtained for the uncoated devices! We do not quite know why this is the case and we primarily attribute this to the fact that the silicone rubber is not applied or cured in a careful manner. It should be noted that our primary reason for applying the silicone coating was to demonstrate that indeed the dissolution of the polysilicon coating could be slowed down. Another possible explanation is that when applying the coating on the device, we introduce a new mechanism (degradation of the coating and diffusion through it) which is added to the previous mechanisms contributing to the degradation and eventual leakage of the package. At high temperature, this mechanism is one of the dominant mechanisms, which means that the time necessary to overcome the coating barrier is dominant in the overall MTTF. However, the activation energy (Q) of this added mechanism is small compared to the etching of the top polysilicon layer, which was the only major mechanism observed for the uncoated devices. Thus, calculating a single activation energy for the 2 mechanisms would lead to a prediction dominated by the better barrier at high temperature, which would be wrong. Indeed, because of the difference in the activation energies, the coating is an efficient barrier at high temperature compared to the bonding barrier, but the acceleration factor for the coating is very small compared to the one for the bonding barrier. Thus, we should be careful in our calculations not to emphasize the silicone coating barrier, but to separate the two mechanisms, which are the degradation of the silicone coating and the bonding barrier.

We will be conducting additional tests on coated packages and will improve the coating process so that a more reliable set of measurements can be obtained.

2.1.5 Ongoing Room Temperature Soak Tests in Saline

The packages soaked in saline at room temperature have been under test close to 4 years. We originally started these soak tests to complement the accelerated soak tests at the higher temperatures. We have consistently observed in these tests that at room temperature we are below the activation energy required to cause dissolution and hence we have not yet observed any dissolution related failures. This result is in accordance with the acceleration model used in interpreting the high temperature tests. Indeed, it seems to confirm that the activation energy for the dissolution of the substrate or the top polysilicon is high. Thus, if the dissolution has an effect at high temperature, it may not be significant at body temperature, because of an exponential decrease of the acceleration factor with temperature.

Indeed, out of the original 6 packages, one failed prematurely the first day and one failed because of mishandling. The 4 other devices are still under test and present no sign of leakage into the capsule after being soaked for 1344 days. Table 7 summarizes the pertinent data from these soak tests.

Table 7: Data for room temperature soak tests in saline.

Number of packages in this study	6
Soaking solution	Saline
Failed within 24 hours (not included in MTTF)	1
Packages lost due to mishandling	1
Longest lasting packages in this study	1344 days
Packages still under tests with no measurable room temperature condensation inside	4
Average lifetime to date (MTTF) so far including losses due to mishandling	*1100 days*
Average lifetime to date (MTTF) so far not including losses due to mishandling	*1344 days*

2.2 The Relative Humidity Sensor

In the previous progress report, we discussed the design of a relative humidity sensor (RHS) to be used in monitoring moisture inside the glass-silicon packages implanted in animals. The requirements for this sensor include : (a) withstand package sealing process (anodic bonding: 320° C, 30 minutes); (b) be small enough to fit into the Silicon-Glass package (1.8mm x 9 mm); (c) provide high sensitivity; and (d) show little or no drift during operation at 37° C since calibration is not possible after sealing. In the previous quarter, we completed the design of the sensor. The specifications of this sensor are shown in the Table 8.

Table 8 : The properties of the relative humidity sensor.

Moisture Sensing Material	CU1512, Polyimide
Capacitor Plate Area	1 mm^2
Effective Area	0.5 mm^2
Thickness	0.1 μm
Capacitance (0% RH)	146 pF
Capacitance (100% RH)	173 pF
Sensitivity	0.7pF / %RH

The sensor is a parallel plate capacitive type humidity sensor in which a polyimide layer is used as the capacitor dielectric and is the humidity sensing material . The fabrication of the polyimide relative humidity sensor starts by growing an oxide layer for isolation (1μm) on a silicon substrate as seen in Figure 9. The following step is the deposition and patterning of the first metal electrode (Al, 0.3μm). The polyimide (CU1512, Dupont) is next spun and cured at 300°C, and is then patterned using reactive ion etching. The final step is the deposition and patterning of the top electrode (Al, 0.3μm). Figure 10 shows an optical view of a completed relative humidity sensor. The top metal is interdigitated with 20μm line and 20μm spacing to allow moisture diffusion into the humidity sensitive polyimide layer. Sensors with 300Å, 660Å and 1200Å thick polyimide have been fabricated and tested inside a humidity chamber using a capacitance meter at 1 MHz as the relative humidity varied from 30% to 70%.

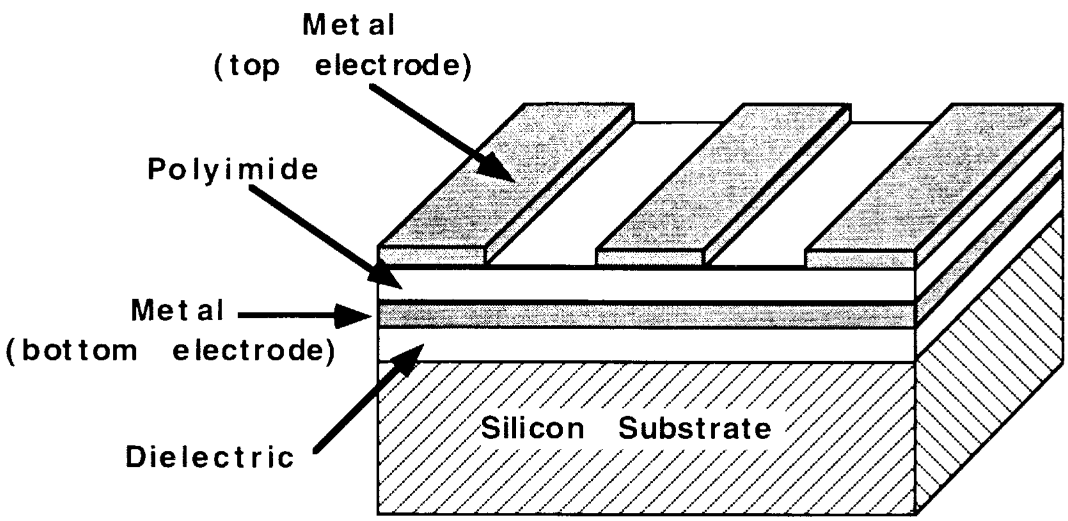

Figure 9: The cross sectional view of a polyimide parallel plate type capacitive sensor.

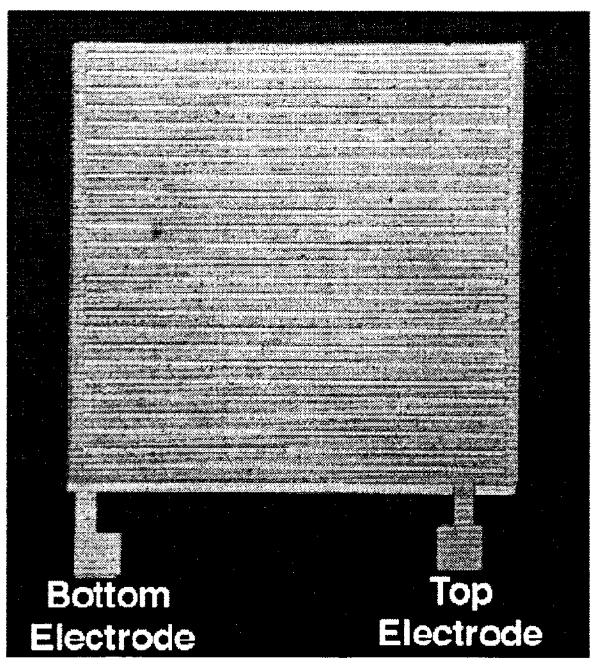

Figure 10: Top view of a fabricated relative humidity sensor. Device is 1mm on a side.

The RHS has been subjected to a set of extensive tests. The sensors are first exposed to the extreme anodic bonding conditions of 400 C for 1 hour and then wire bonded to printed circuit board for testing and inside a humidity chamber (ESPEC). The temperature is set to body temperature (37°C) and the humidity was swept from 30% to 70%. Figure 11 show results from a 1200A thick device. After having success with this device, we next fabricated sensors with much thinner polyimide film (thicknesses of 660A and 300A). All of the 660A thick devices survived after the anodic bonding test, and the yield from the 300A devices was about 70%, which is still quite high and acceptable. The lower yield for the thinner devices is caused by shorts between the two metal electrodes through pinholes in the polyimide. Figure 12 shows results from a 300Å thick device after exposure to anodic bonding conditions. The results are summarized in Table 9 below. As expected the thinner devices have a higher sensitivity than their thicker counterparts. The sensor are very linear and show a nonlinearity of less than 1%RH.

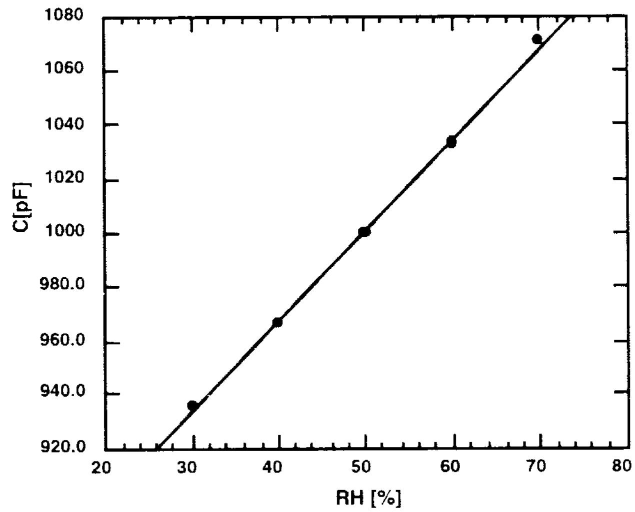

Figure 11: Test results from a 1200Å thick relative humidity sensor.

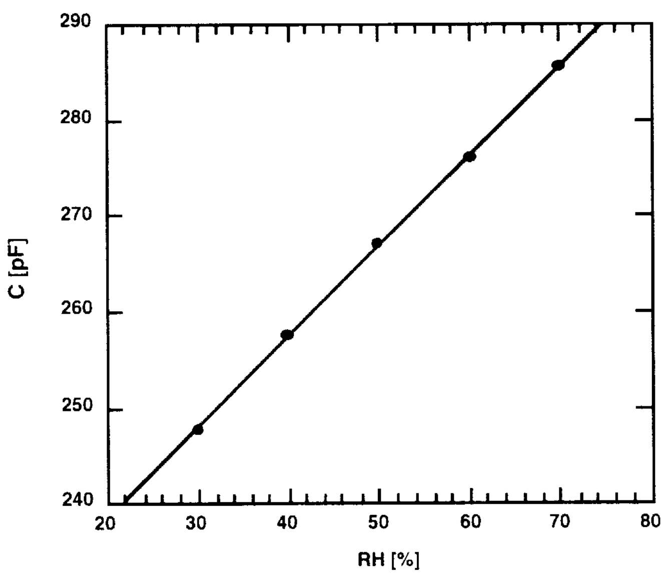

Figure 12: Test results from a 300Å thick relative humidity sensor.

Table 9: Measured sensitivity for various polyimide thicknesses.

Spin Speed (rpm)	Thickness (A)	Capacitance (Calculated, pF)	Capacitance (Measured, pF)	Sensitivity (Measured, pf/%RH)
4000	298	1083	1300	3.4
2000	649	498	544	1.7
2000 (twice)	1208	267	275	0.86

The sensors will be eventually encapsulated inside the package using the anodic bonding process. Once encapsulated they will not be accessible for re-calibration, which means that the sensors should show little or no drift during operation. Hence, we have tested the sensor at 37° C for 48 hours at 50% relative humidity. The result from this test is shown in Figure 13. As seen from the figure there is very little drift (less than 1%RH) in the sensor. The fact that there is little drift is very promising and suggests that we should be able to use these devices for monitoring humidity inside the package.

We have also performed tests to characterize device hysteresis. At 37° C, a 1200Å-thick sensor was cycled from 30% to 70% RH and then down to 30% RH in 10%RH steps. As seen in Figure 14, the sensors do display some hysteresis, but it is very small being less than 2%RH. It should also be mentioned that we believe some of this is due to the measurement system. In addition, the drift issue is more crucial and hence we will perform more drift studies at different temperatures with different relative humidity levels prior to incorporating the sensor into the package.

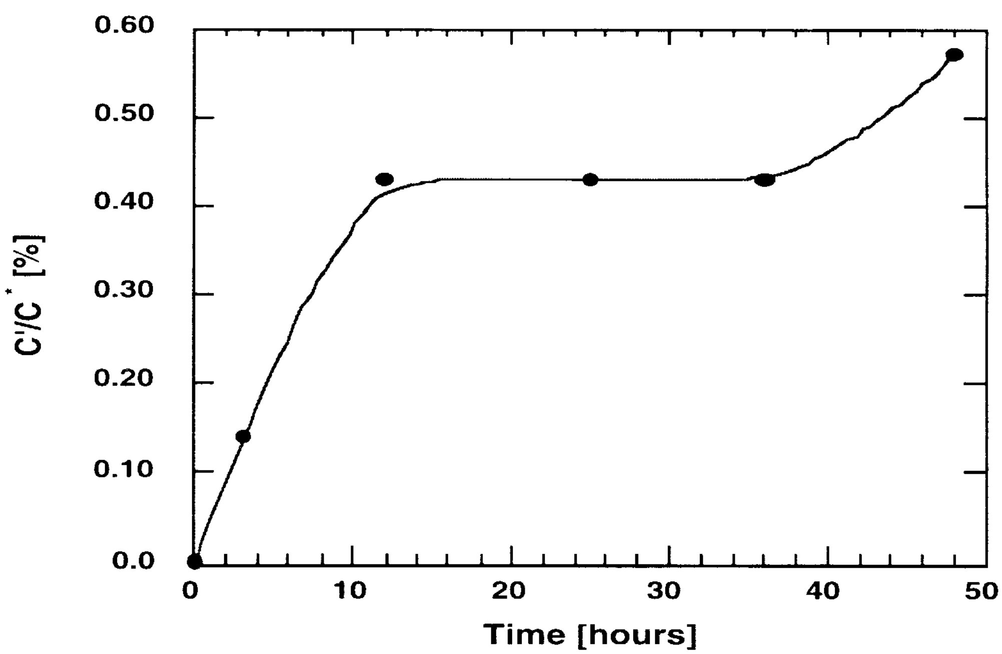

Figure 13: Drift measurement results for 48 hours at 37° C in 50% RH; C' is the change in capacitance and C* is the full-scale capacitance change.

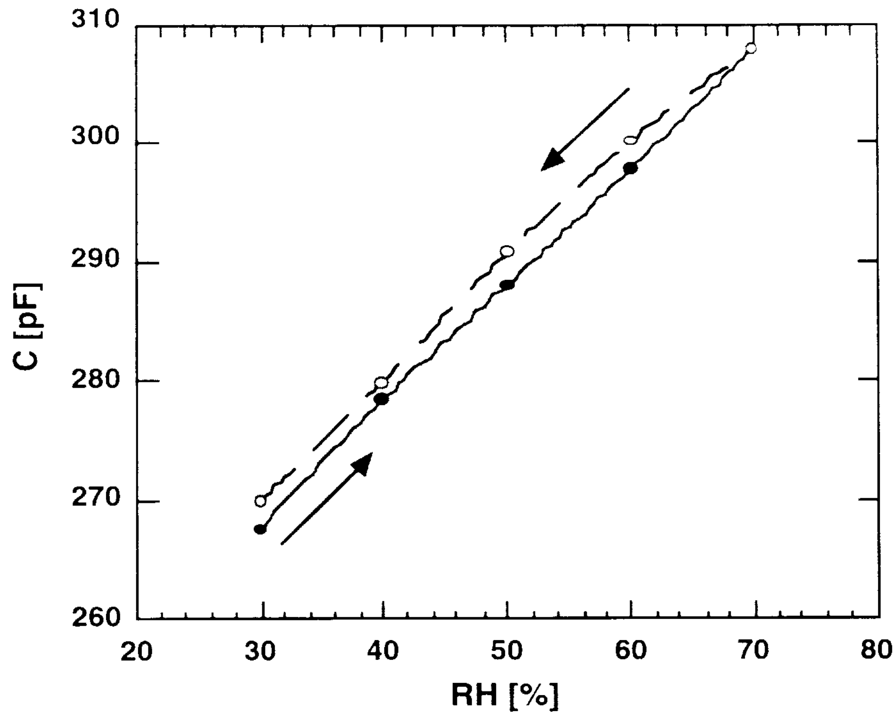

Figure 14: Measured device hysteresis at 37°C for the 1200Å thick relative humidity sensor.

2.3 Telemetry Monitoring of Dew Point Inside the Package

One limitation of our current testing procedure, which consists of testing the dew point sensors by probing the external pads, is the fact that this electrical testing is impossible once the probing pads dissolve or are covered with salt deposits. We then have to rely on visual observation to determine when failure occurs. Another limitation is the fact that for testing, each device has to be handled separately, which is both time consuming and also increases the chances of mishandling which can lead to failure. In order to overcome those limitations, we have been working on a telemetry measurement technique of dew point inside the package, as shown in Figure 16.

In the last progress report, the theoretical modeling of telemetry measurement was discussed. In the beginning of this past quarter, more preliminary experiments were performed enhance our understanding of the measurements. One of the issues to be overcome before proceeding further s the fact that when water is present inside the external coil, the external measured impedance was significantly reduced, thus reducing the coupling between the two coils. After making some measurements on many different types of external coils, it has been found that by using a multiple layer coil this problem could be overcome. A layout of integrated coils with different parameters (number of turns, widths of each turn and spacing between the turns) has been designed and the corresponding single mask has been fabricated. The integrated coils are currently in fabrication and should be ready at the beginning of the coming quarter.

It should also be mentioned that the main use of this passive telemetry approach is for in-vitro testing. However, the same approach can be potentially used to monitor humidity changes inside the package in animals. Another advantage of this system is that it should allow us to test a large number of devices in batch.

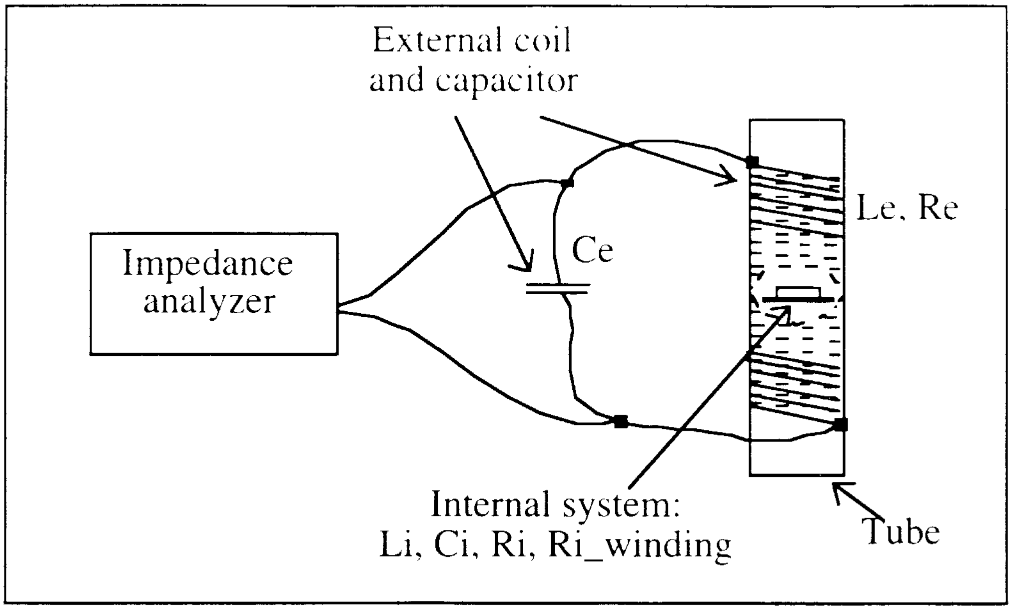

Figure 16: Passive telemetry system for monitoring humidity changes inside the package.

III. PLANS FOR THE COMING QUARTER

In the coming quarter we will continue our activities in several areas. The accelerated tests in saline have come to an end. As such we have started to fabricate a new set of packages and expect to start some new soak tests in saline during this quarter. We will also fabricate more relative humidity sensors and continue with the tests especially in the area of drift studies at higher temperatures. We will begin to characterize polysilicon etching in saline at high temperatures and try to prevent this etching using other methods in addition to silicone rubber coatings. The activities in the areas of development of remote telemetry monitoring and the silicon to silicon bonding utilizing eutectic bonds will also be continued.